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ELECTRONS OF NATURAL ORIGIN IN THE INNER
RADIATION ZONE

by

V. V. Temnyy

(USSR)

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ELECTRONS OF NATURAL ORIGIN IN THE INNER
RADIATION ZONE

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by V. V. Temnyy

SUMMARY

Following were the characteristics of stationary distribution of electrons of natural origin in the inner radiation zone, with energy > 40 kev: on the basis of measurements on AES Kosmos-3 and -5 in 1962 and Elektron-1 and -3 in 1964:

- the presence of intensity maximum ($2 \cdot 10^9$ electron/cm².sec in the equatorial plane between $L = 1.6$ and 1.8 ;
- the dependence of intensity on parameters L and B over drift trajectories with $h_{min} > 700$ km and longitudinal dependence of intensity on trajectories with $h_{min} < 700$ km;
- the rate of losses from the region of maximum trapping is equal to $2 \cdot 10^{-8}$ electron/cm³.sec.

On the basis of comparison of the obtained distribution of electrons with 11 measurements of electrons on various satellites and rockets, conducted from 1958 through 1966, the conclusion could be drawn about the stability of intensity of electrons of natural origin in the inner radiation zone in the course of the 11-year cycle of solar activity.

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Numerous measurements of particles trapped in the inner radiation zone have shown that their intensity undergoes no significant temporal variations in the inner zone as it does in the outer zone. For that reason it became possible to obtain a stationary pattern of intensity distribution of trapped protons with various energies. No analogous distribution of trapped electrons has been obtained to date. This is explained by experimental difficulties of measurement of electron fluxes against the background of high energy protons and by substantial variations of fluxes and spectra of electrons of the inner zone after the high-altitude thermonuclear explosion conducted by the U.S.A.

on 9 July 1962 [1]. The period during which the investigation of electrons of natural origin against the background of those of artificial origin will be made substantially difficult is estimated by some authors as being of 20 to 30 years [2, 3].

It was found in reality that the distribution of electrons of natural origin could have been obtained as early as one year and one half after the explosion, considering fluxes with energy of 40 kev and higher, and utilizing the available data on their spectra. We utilized as initial data, on the basis of which the distribution of electron fluxes of the indicated energy were obtained in the inner zone, the results of measurements obtained prior to the explosion of 9 July 1962 on AES Kosmos-3 and Kosmos-5 [4 - 6] and in 1964 on AES Elektron-1 and Elektron-3 [7, 8]. The utilization of these alternative results of measurements, obtained in different conditions (prior to and after the explosion of 9 July 1962), was found to be possible for the construction of a model distribution of electrons, for it was established that on shells $L > 1.4$ the distribution of fluxes in 1964 did not differ from those obtained in 1962. On the basis of the model constructed it is possible to obtain such properties of the trapped electron component as the intensity variation along L , the losses from the trapping region, the power of the source sustaining the stationary distribution in the presence of losses. Finally, when comparing the results that were obtained in other experiments at electron variation between 1958 and 1966 with the model, it becomes possible to appraise the degree of stability of the inner zone in the course of the solar activity cycle.

Model Distribution of Electrons with $E > 40$ kev According to Data
of AES Kosmos-3, Kosmos-5, Elektron-1 and -3

The measurements of trapped electrons with energy $E > 40$ kev completed in the inner zone prior to 9 July 1962 on Kosmos-3 and Kosmos-5 [4 - 6], were conducted at altitudes to 1600 km. As a result, a distribution of fluxes of the natural electron component in a substantial region of (B, L) -space. This intensity of electrons is unambiguously characterized by parameters B, L on those drift trajectories not descending in the region of the South Atlantic anomaly below 700 km. For lower trajectories with identical values of parameters B, L , the intensity depends also on the longitude of the place of registration [9, 10].

Measurements of electrons on AES Elektron-1 and -3 were conducted in 1964 at altitudes from 400 to 7000 km. On the basis of measurements conducted, fluxes of electrons with $E > 1.1$ Mev, of artificial origin were separated from the registered fluxes of electrons with $E \geq 40$ kev [11]. The distribution of the obtained fluxes of electrons with energy from 40 kev to 1.1. Mev was plotted in coordinates (B, L) [7, 8]. When comparing this distribution with that obtained from data of Kosmos-3 and -5, it was found that in overlapping regions of (B, L) -coordinates, the intensities of electrons registered in 1964, and those of natural origin registered in 1962, are identical with a precision not worse than 50 percent. Besides, in these alternate measurements the quantities $d \ln I / dB$ along identical L are equal.

Consequently, the intensity distribution along identical L were identical at the beginning of 1962 and in 1964 in the whole inner zone, and this is why electrons with energies to 1.1 Mev, registered on Elektron-1 and -3, had a natural origin. Fig.1 can serve as illustration of the comparison of results of measurements of 1962 and 1964, in which plotted are separate values obtained on Elektron-1 and the averaged course of intensity variation according to data from Kosmos-3 and -5, constructed for the center of the South Atlantic anomaly ($\Delta\lambda = 0^\circ$) and for $\Delta\lambda = -100^\circ$, where $\Delta\lambda$ is the distance along the longitude from the center of the South Atlantic anomaly.

The total pattern of intensity distribution of natural electrons with $E \geq 40$ kev in the inner zone, obtained on the basis of measurements on AES Kosmos-3 and -5 and Elektron-1 and -3 is shown in Fig.2.

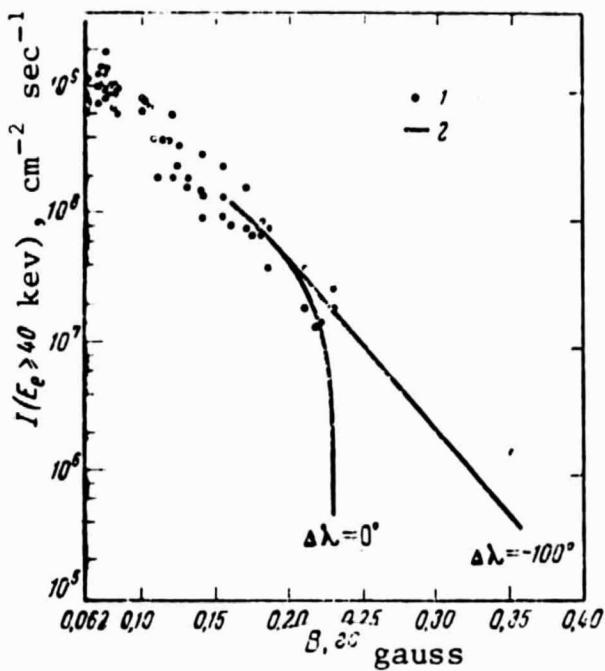


Fig.1. Variation of fluxes of electrons with $E \geq 40$ kev along $L = 1.7$, as a function of magnetic field intensity B , gauss

1) Elektron-1; 2) Kosmos-3, -5

It follows from it that the region of intensity maximum is in the equatorial plane on $1.6 \leq L \leq 1.8$.

From an earlier conducted analysis [10], it follows that for all L , corresponding to the inner zone, the longitude dependence is identical along the drift trajectories passing at an identical minimum altitude above the Earth's surface in the region of the anomaly ($h_{\min} = \text{const}$). The averaged longitude dependence for several values of h_{\min} is plotted in Fig.3.

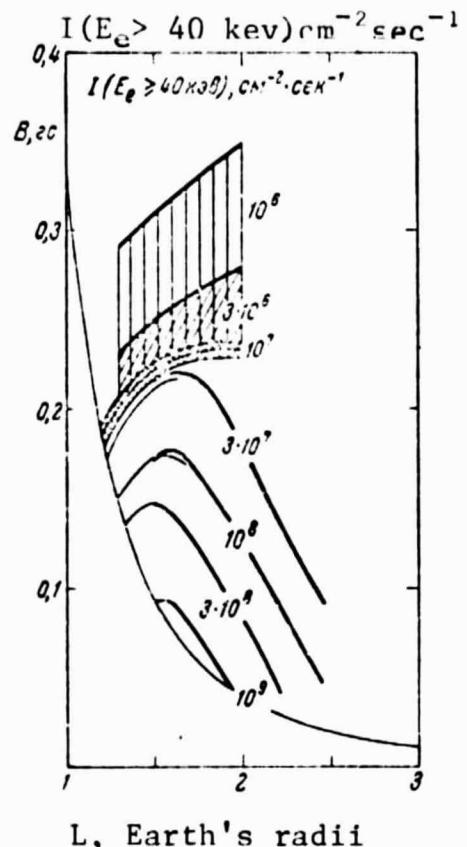


Fig.2. Distribution of fluxes of electrons with $E \geq 40$ kev in the inner zone, obtained on the basis of measurements on Kosmos-3 and -5, Electron-1 and -3. A longitude dependence exists in the shaded portions of the drawing

TABLE 1

SPACECRAFT	L	B, gauss
<u>Explorer-4</u> [12] 1 - 16 August 1958 $I(E_e > 20 \text{ kev}) = (0.1 - 76) \text{ erg/cm}^2 \cdot \text{sec} \cdot \text{ster}$	1.32 - 1.47	0.14 - 0.22
<u>Rockets Javelin</u> [13, 14] Febr. - August 1959 $I(E_e > 30 \text{ kev}) = 9.25 \cdot 10^3 \text{ el/cm}^2 \cdot \text{sec} \cdot \text{ster}$ kev	1.305	0.197 $\Delta\lambda = -20^\circ$
<u>Tsju-1</u> [15] 16 Jul - 10 August 1961 $I(E_e > 40 \text{ kev}) = 1.0 \cdot 10^7 \text{ cm}^{-2} \cdot \text{sec}^{-1}$	1.20 - 1.32	0.176 - 0.193
<u>Telstar-1</u> [16] 22 - 26 July 1962 $I(E_e = 420 - 640 \text{ kev}) = 1.5 \cdot 10^8 \text{ cm}^{-2} \cdot \text{sec}^{-1}$	1.8	$B/B_0 = 1$
<u>1962 Bk</u> [17] October-November 1962. $I(E_e > 325 \text{ kev}) = (10^4 - 6 \cdot 10^5) \text{ cm}^{-2} \cdot \text{sec}^{-1} \cdot \text{ster}^{-1} \cdot \text{kev}^{-1}$	1.25 - 1.7	0.07 - 0.20
<u>Kosmos-17</u> [18] May 1963 $I(E_e > 80 \text{ kev}) = 10^7 \text{ cm}^{-2} \cdot \text{sec}^{-1}$	1.5	0.20
<u>Explorer-14</u> [19] October 1962 $I(E_e > 50 \text{ kev}) = (1 - 2) \cdot 10^9 \text{ cm}^{-2} \cdot \text{sec}^{-1}$	2.0	$B/B_0 = 1$
<u>O.G.O</u> [20 - 22] September-October 1964 $I(E_e > 50 \text{ kev}) = (10^7 - 10^9) \text{ cm}^{-2} \cdot \text{sec}^{-1}$	1.4 - 2.5	from $B/B_0 = 1$ to that corresponding to $h_{\min} = 100 \text{ km}$
<u>1964-45 A</u> [23] August 1964 $I(E_e > 170 \text{ kev}) = 3 \cdot 10^5 - 1.5 \cdot 10^7 \text{ cm}^{-2} \cdot \text{sec}^{-1} \cdot \text{sterad}^{-1} \cdot \text{Mev}^{-1}$	1.23 - 2.6	0.112 - 0.232
<u>1966-70 A</u> [24] August-September 1966 $((E_e > 300 \text{ kev}) = 5 \cdot 10^3 - 1.3 \cdot 10^5) \text{ cm}^{-2} \cdot \text{sec}^{-1} \cdot \text{sterad}^{-1} \cdot \text{kev}^{-1}$	1.28 - 2.25	0.06 - 0.17

Therefore, knowing parameters L, B, and $\Delta\lambda$ of the place of registration, it is possible to determine the intensity of trapped (or quasi-trapped) electrons at any spot of the inner zone.

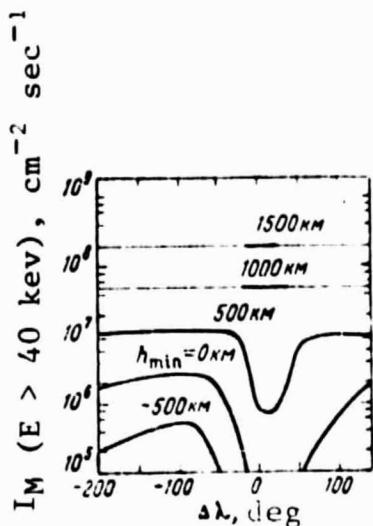


Fig. 3

Averaged longitude dependence of intensity along the drift trajectories for a few h_{\min} , obtained on the basis of measurements on artificial satellites Kosmos-3 and Kosmos-5

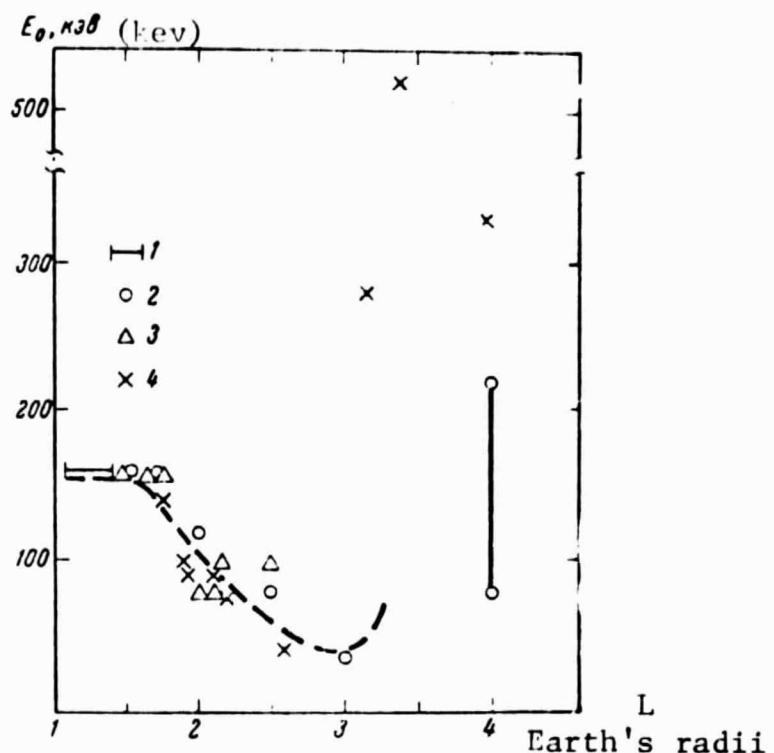


Fig. 4. Values of E_0 characterizing the spectra of electrons $I \sim \exp(-E/E_0)$ in the inner zone obtained in a few experiments and averaged dependence $E_0(L)$, utilized at computations (dashed line)

1) INJUN-1; 2) O.G.O.-1; 3) 1962 βκ; 4) 1964-45A

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COMPARISON OF THE DIFFERENT MEASUREMENTS OF ELECTRONS IN THE INNER ZONE WITH THE MODEL PRESENTED

For the period of measurements on each of the 4 satellites in question no temporal variations of electron fluxes were observed even during powerful magnetic disturbances [7]. Besides, in 1964 the distribution of electron intensity was the same as in 1962. This is why it is possible to appraise the degree of stability of electron fluxes in the inner zone for a more prolonged period, comparing the fluxes registered in other experiments conducted in 1958, with the model ones. The compilation of such a comparison of results is made in the Table 1 [preceding page], where we indicated the the period of registration of electrons with indication of their energy, the parameters L and B and, in case of necessity $Δλ$ too.

On the basis of the values utilized we computed the omnidirectional fluxes of electrons I_{comp} ($E \geq 40$ keV) $\text{cm}^{-2} \text{ sec}^{-1}$ taking into account their degree of anisotropy at the given spot. The transition to fluxes with threshold energy of 40 keV was materialized account being taken of the fact that the spectrum of the trapped electrons has an exponential form $dI/dE \sim \exp(-E/E_0)$ and E_0 is dependent on L. The averaged dependence $E_0(L)$, utilized during computations, is shown by the dashed line of Fig.4. It is based upon mutually agreeing values of several spectrum measurements [17, 20, 22, 24].

The values of the computed computed to model fluxes' ratio $K = I_{\text{comp}}/I_{\text{mod}}$ for $E_e \geq 40$ kev, utilized for the estimate of the stability of the inner zone are plotted in Fig.5 hereafter.

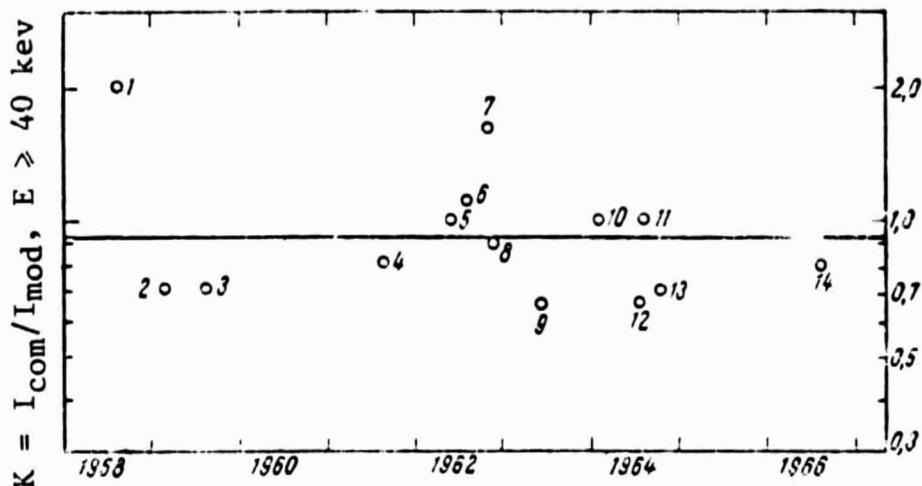


Fig.5. Results of comparison of fluxes of electrons registered in various experiments with the model distribution :

- 1) Explorer-4; 2), 3) "Javelin" rockets, 4) Injun-1; 4) Kosmos-3; Kosmos-5; 6) Telstar-1; 7) Explorer-14; 8) AES 1962 B κ ; 9) Kosmos-17; 10) Elektron-1; 11) Elektron-3; 12) AES 1964-45 A; 13) AES O.G.O.-1; 14) AES 1966-70 A. The averaged dependence $\bar{K} = 0.92$ was obtained according to all the 14 values

It was found according to these values that the mean value $K = 0.92$. Then for the estimates of possible intensity variations in the course of the 11-year cycle of solar activity, the temporal course of intensity, shown in Fig.5, was approximated by the equation

$$\lg K = \lg \bar{K} + \mu \sin\left(\frac{\pi}{2} + \frac{2\pi}{11}t\right),$$

where $\bar{K} = 0.92$, $0 \leq t \leq 11$, $t = 0$ is the beginning of 1958, μ varied within the limits $+0.6 \leq \mu \leq -0.6$. The best approximation was considered to be the one for which

$$\sum_{i=1}^n |\lg K_i - \lg \bar{K}|$$

reached its minimum value. It was found that this condition is satisfied by the approximation at which $\mu = 0$. This means that the intensity in the inner zone remained constant from 1958 through 1966.

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LOSSES OF ELECTRONS FROM THE REGION OF TRAPPING

The appearance of quasi-trapped particles on lower drift trajectories leading to longitude dependence of intensity, are usually interpreted as a result of lowering along L of mirror points of trapped particles [9, 10, 18, 25], whereupon it is considered that particles descending to lower h_{\min} are absorbed in the atmosphere. Therefore, the losses of trapped particles can be appraised by the longitude dependence.

In order to conduct the indicated estimates on the basis of the results of measurements on Kosmos-3 and -5, we shall conditionally subdivide here the entire longitude interval into two segments: the first in 260° (from $\Delta\lambda = 0$ to -100°) and the second in 100° (from $\Delta\lambda = -100^\circ$ to 0°). It follows from Fig. 3 that in the course of drift motion of electrons along the first segment of longitudes intensity increase on low drift trajectories takes place ($h_{\min} < 700$ km); as to the second segment of longitudes, there takes place absorption of accumulated flux in the atmosphere as the height of drift trajectories decreases. The maximum observed intensity variations along the drift trajectory constitute $1.5 \cdot 10 \text{ cm}^{-2} \text{ sec}^{-1}$. If the downward shift of mirror points has in the second longitude interval the same velocity as in the first one, there must be absorbed in it not only the flux having arrived on lower drift trajectories during the period of their longitudinal drift through the first segment, but also during the drifting period of the second segment, i. e.

$$\Delta I = \Delta I_{\text{obs}} \frac{360^\circ}{260^\circ} \approx 2 \cdot 10^7 \text{ electron/cm}^2 \cdot \text{sec.}$$

Apparently, this is the lower estimate of losses, since particle absorption in the atmosphere of the first segment was not considered.

It was found earlier that the intensity of electrons in the inner zone is constant. This means that there exists a source compensating the losses. Its power on the equator may be estimated taking advantage of the well known relation

$$P[\text{electron/cm}^3 \cdot \text{sec}] = \frac{\Delta I}{T_{\text{dr}} v_e} - \frac{B_{\text{equ}}}{B_{h_{\min}}} = 100 \text{ km}$$

where ΔI is the flux being lost for one drift revolution, T_{dr} is the period of electrons' drift around the Earth, v_e is the velocity of electrons, $B_{\text{equ}}/B_{h_{\min}} = 100$ km is the ratio of magnetic field intensity at the equator to that in the region of losses at minimum altitude of 100 km. It was obtained that at the equator at the center of the inner zone ($L = 1.6$), $P = 2 \cdot 10^{-8} \text{ electron/cm}^3 \cdot \text{sec}$ for electron energy of 100 kev, which is approximately by 4 orders greater than the power of the source from β -decay of neutron albedo [26]. Analogous calculations for other L-shells show that the power of the source from β -decay of neutrons is also negligibly small in the entire inner zone. The values of the source's power obtained from the data of Kosmos-3 and -5 agree well with those found by Williams and Kohl [27] on the basis of longitude dependence for $E_e > 280$ kev on $L = 2$. They found $P = (4 \cdot 10^{-8} - 4 \cdot 10^{-9}) \text{ cm}^3 \text{ sec}^{-1}$. These results show

that the entire inner zone is filled by the source, having not only a softer spectrum than at β -decay of neutrons [28], but also a power substantially higher than the neutron.

The most thoroughly studied mechanism of electron losses from the inner zone is the Coulomb scattering. This is why the time constants τ , during which the intensity in the equatorial plane would have decreased by e times (i. e. by the quantity $0.63 I_{\text{equ}}$) at the obtained constant losses P , must be determined for the evaluation of its role. To that effect we shall take advantage of the relation

$$\tau = \frac{0.63 I_{\text{equ}}}{I} \frac{B_{\text{hmin}} = 100 \text{ km}}{B_{\text{equ}}} T_{\text{dr}}.$$

Then we shall compare τ with τ_{Coulomb} , i. e. the time constants of intensity decrease at the expense of Coulomb scattering.

The obtained values of τ are compiled in Table 2 for a few L . As earlier we considered electrons with energies of 100 kev. For comparison we brought out the values of time constants for electron losses of same energy at the expense of Coulomb losses. They are usually determined by way of solution of the Fokker-Planck equation taking into account the simultaneous decrease of energy and pitch-angles at scattering. Such calculations were performed by Walt [29] for electrons with $E \approx 1$ Mev. In order to determine τ_{Coulomb} for electrons with energy of 100 kev, we utilized the results of calculations performed in [30], from which it follows that $\tau_{\text{Coulomb}} \sim E^{1.5}$. When comparing with τ_{Coulomb} ($E_e = 100$ kev) it becomes evident that the intensity drop resulting in longitude dependence, takes place much more rapidly than in the case of Coulomb scattering.

T A B L E 2

L	$\tau, \text{ sec}$	$\tau_{\text{Coul}} (E_e = 100 \text{ kev})$ sec	$\tau_{\text{Coul}} (E_e = 1 \text{ Mev})$ sec
1.25	10^5	$1.5 \cdot 10^6$	$5 \cdot 10^7$
1.3	$2 \cdot 10^5$	$3 \cdot 10^6$	$9 \cdot 10^7$
1.4	10^6		
1.5	10^6	$1.5 \cdot 10^7$	$5 \cdot 10^8$
1.8	$2 \cdot 10^6$		
2.0	$2 \cdot 10^6$		

It is evident that on $L > 1.5$, the departure from τ_{Coulomb} is still greater, for the latter increases with altitude, while τ remains practically constant.

In the above-made estimates of losses there still is an uncertainty due to the fact that the energy of electrons is not known with sufficient precision. For example, for a spectrum of electrons of the form $dI/dE \sim \exp(-E/160 \text{ kev})$ it is appropriate to choose for average energy 160 kev. However, for greater energy the difference between τ and τ_{Coulomb} will be still greater, for as energy increases, τ decreases ($\tau \sim T_{\text{dr}}$), while τ_{Coulomb} to the contrary increases. Thus,

even with a substantial uncertainty in the selection of the value of mean energy of electrons, the conclusion that there exists an additional mechanism of electron losses from the region of trapping, remains valid. Analogous results were also obtained during the investigation of losses of high-energy electrons on $L > 1.4$ injected during the explosion "Maritime Star" [29].

The analysis conducted shows that the distribution of fluxes of electrons with $E > 40$ kev in the inner zone, obtained on AES Kosmos-3, Kosmos-5, Elektron-1 and Elektron-3, is characterized by a long-term stability. The power of the unknown source, refilling or replenishing the losses from the region of capture, is substantially higher than the β -decay of albedo neutrons, whereas the losses significantly exceed, in their turn, the Coulomb losses. The fluxes of particles registered in the inner zone are lower than those which are threshold on account of trapped electrons' interactions with atmospheric whistlers.

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 VOLT TECHNICAL CORPORATION
 1145 - 19th St.NW
 WASHINGTON D.C. 20036
 Tel: 223-6700 (X-36, 37)

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